NASA/TM—2014-218295 AIAA–2014–0689

Lunar Polar Environmental Testing: Regolith Simulant Conditioning

Julie E. Kleinhenz
Glenn Research Center, Cleveland, Ohio

May 2014

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2014-218295 AIAA–2014–0689

Lunar Polar Environmental Testing: Regolith Simulant Conditioning

Julie E. Kleinhenz
Glenn Research Center, Cleveland, Ohio

Prepared for the
SciTech 2014
sponsored by the American Institute of Aeronautics and Astronautics
National Harbor, Maryland, January 13–17, 2014

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

May 2014

Acknowledgments

This work is supported by the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) project under the Advanced Exploration Systems (AES) program. The auger used in this test program was graciously supplied by the Canadian Space Agency, and the author would like to thank them for their support.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

Lunar Polar Environmental Testing: Regolith Simulant Conditioning

Julie E. Kleinhenz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

As In-Situ Resource Utilization (ISRU) system development approaches flight fidelity, there is a need to test hardware in relevant environments. Extensive laboratory and field testing have involved relevant soil (lunar regolith simulants), but the current design iterations necessitate relevant pressure and temperature conditions. Including significant quantities of lunar regolith simulant in a thermal vacuum chamber poses unique challenges. These include facility operational challenges (dust tolerant hardware) and difficulty maintaining a pre-prepared soil state during pump down (consolidation state, moisture retention).

For ISRU purposes, the regolith at the lunar poles will be of most interest due to the elevated water content. To test at polar conditions, the regolith simulant must be doped with water to an appropriate percentage and then chilled to cryogenic temperatures while exposed to vacuum conditions. A 1 m tall, 28 cm diameter bin of simulant was developed for testing these simulant preparation and drilling operations. The bin itself was wrapped with liquid nitrogen cooling loops (100 K) so that the simulant bed reached an average temperature of 140 K at vacuum. Post-test sampling was used to determine desiccation of the bed due to vacuum exposure. Depth dependent moisture data is presented from frozen and thawed soil samples.

Following simulant only evacuation tests, drill hardware was incorporated into the vacuum chamber to test auguring techniques in the frozen soil at thermal vacuum conditions. The focus of this testing was to produce cuttings piles for a newly developed spectrometer to evaluate. This instrument, which is part of the Regolith and Environmental Science Oxygen and Lunar Volatiles Extraction (RESOLVE) program science hardware, detects water signatures from surface regolith. The drill performance, behavior of simulant during drilling, and characteristics of the cuttings piles will be offered.

Nomenclature

DT	Drill Test
ISRU	In-Situ Resource Utilization
NIRVSS	Near-Infrared Volatile Spectrometer System
RESOLVE	Regolith and Environmental Science Oxygen and Lunar Volatiles Extraction
ST	Soil Test

Introduction

Development of hardware for extraterrestrial environments is a highly iterative process, requiring testing and validation in relevant environmental conditions. This is especially true for In-Situ Resource Utilization (ISRU) applications where a wide variety of components and instruments will be exposed to harsh environments for an extended period of time.

One key resource for ISRU is water bound in extraterrestrial surface material, or regolith. On the moon, science missions such as LCROSS (Ref. 1) have shown evidence of 5.6 percent ice water (by mass) at the lunar polar regions. In order to verify this, the Regolith and Environmental Science Oxygen and Lunar Volatiles Extraction (RESOLVE) project is underway. This potential lunar prospector aims to 'ground-truth' the existence of water using a rover with a drill and science hardware. This project has gone through

several hardware iterations including laboratory and field tests using lunar regolith simulants. Component testing with regolith simulant in relevant thermal and vacuum environments has begun.

Using regolith simulant in a vacuum chamber presents several unique challenges. Not only does the particulate matter pose a risk to the vacuum chamber hardware (pumps and instruments), the regolith simulant itself has a tendency to off-gas violently during the pump down process. This results in soil movement, including spouts that result in airborne particles, that disturbs the compaction and pre-preparation of the soil bed. Previous publications (Refs. 2 and 3) have discussed these behaviors in small and large scale soil beds. The off-gas disturbances can be mitigated by regulating the pump rates to keep the pressure decay very slow. The exact rates and pressure ranges vary based on the soil bed condition, but circumstantial data about off-gassing will be offered later in this document.

Along the same vein, chamber evacuation will result in moisture loss from the pre-prepared regolith simulant. Methods of preparing the regolith simulant, including moisture addition and compaction, have been discussed in Reference 4. In this study, the moisture doped regolith simulant was cryogenically frozen in a vacuum environment. Lacking a good method for measuring soil moisture content, in-situ and in a vacuum, the simulant was sampled pre- and post- vacuum to determine desiccation during exposure.

This information and simulant preparation methods were then used to conduct the first “dirty” thermal-vacuum tests of RESOLVE component hardware. These tests involved drilling into cryogenically frozen, moist simulant at thermal-vacuum conditions. An auger tool developed for RESOLVE field testing was provided by partners at the Canadian Space Agency and used to drill 50 cm into a bed of LHT-3m lunar regolith simulant. The cuttings pile created by drill operations was analyzed using a RESOLVE science instrument, the Near-Infrared Volatile Spectrometer System (NIRVSS), developed at the NASA Ames Research Center. This spectrometer detects water signatures from surface regolith in order to pinpoint water rich locations for detailed soil sampling. Three tests were performed with the drill equipment in the thermal-vacuum, two of which utilized the spectrometer. The vacuum chamber walls were cooled with liquid nitrogen, meaning all hardware was exposed to temperatures of 100 K. The regolith simulant, also cooled with liquid nitrogen, reached temperatures of –130 °C. The vacuum environment was 9×10^{-6} torr.

This document focuses on the behavior of the drilling equipment, vacuum chamber, and soil bed desiccation during these thermal vacuum tests.

Hardware

The thermal vacuum facility, called VF-13, is a vertical cylindrical chamber with an internal volume of 6.35 m^3. The bulk of the volume is within the removable 2.52 m tall by 1.5 m diameter lid. A removable cold wall that fits inside this lid can be used for tests requiring a thermal vacuum. Figure 1 shows the lid as it is being lowered over top of the cold wall. The cold wall is composed of two semi-circular sections, each supplied with its own liquid nitrogen feed. These sections can be controlled separately to mimic the severe temperature gradients on the lunar surface. However, for these tests the two halves were maintained at full liquid nitrogen temperature. The fixed base of VF-13 (shown in Fig. 2 without the lid) is 1.08 m deep and accommodates all the electrical, mechanical, and gas feed-throughs. Four different types of pumps can be used sequentially to achieve a pressure of 10^{-6} torr. Liquid nitrogen is plumbed to the facility to accomplish cryogenic cooling of the simulant bin and the removable cold wall.

The regolith simulant was contained in a cylindrical aluminum bin 1.2 m (48 in.) tall with an inner diameter of 0.278 m (11 in.). The bin height accommodated a 1 m long drill, and the diameter permitted multiple drill holes while keeping heat transfer time (chill down) to a reasonable time frame. The simulant was chilled using liquid nitrogen coolant loops (Fig. 3) clamped to the outside of the bin. Three feed-through ports at various heights along the drill tube accommodated thermocouple probes. Each probe had five type T thermocouples which were embedded in the soil at different radial positions, for a total of 15 thermocouples. These probes were embedded as the bin was filled with simulant, and the simulant was compacted on top of them.



Figure 1.—The VF-13 thermal vacuum facility.

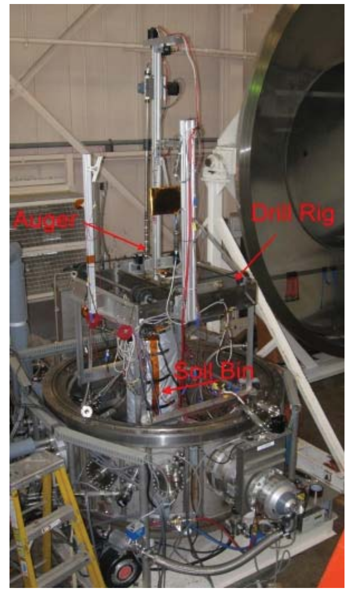


Figure 2.—The drill rig mounted in VF-13 with the chamber lid removed.



Figure 3.—The soil bin with liquid nitrogen cooling loops. The drill rig is mounted above the soil bin.

Three different lunar regolith simulants were used during this test series, GRC3, Chenobi, and LHT-3M. The GRC3 is a lower cost mobility simulant while the latter two are higher fidelity lunar highlands simulants. Before thermal vacuum exposure, the simulant was doped with a known amount of moisture, compacted on a vibration table, and pre-chilled in a commercial upright freezer. The preparation methods are described in a previous publication (Ref. 4). Soil moisture was measured using ASTM D2216 (Ref. 5), which involves baking samples of simulant at 110 °C overnight. All but one test involved a uniform moisture and compaction profile in the simulant bed. One test required a stratified moisture profile with alternating wet (5 percent water by mass) and dry layers. To maintain this stratification, each layer was separated by a barrier of thin aluminum foil. This barrier could be easily and cleanly penetrated with the drill while preventing moisture diffusion between the layers.

The test article, termed the "drill rig", was mounted immediately above the soil bed (Fig. 2). This structure accommodated the 1 m long drill tool. Drill rotation and penetration were driven using geared stepper motors. The drill rig also facilitated lateral movement of the drill assembly so that multiple holes could be achieved. Penetration rate and rotation speed were adjustable. The NIRVSS instrument was mounted on the drill rig so that it had line of sight to the soil bed surface and was consistently lined up with the drill to view the cuttings.

Objectives

The test program covered a total of 6 tests, listed in Table 1. The goal of the first two soil-only tests (ST1 and ST2) was to explore the logistics and desiccation of moist, frozen lunar simulant in a vacuum. This included a functional check out of the new liquid nitrogen cooling system, an examination of the pump down profile with respect to the water phase diagram, determination of time scales for chill-in and pumping, and development of procedures to avoid frost build up and soil disturbances during pump down. The four tests that were part of the NIRVSS instrument test program incorporated the drill hardware. DT0 was an open air test with cryogenically cooled soil. The goal of this test was to do a functional checkout of the drill hardware and drilling parameters. DT1 was a precursor functionality test at thermal vacuum conditions in preparation for the NIRVSS instrument integration. The drill hardware operation was verified at vacuum and the characteristics of the cuttings pile were examined. DT2 and DT3 were performed with the NIRVSS integrated onto the drill rig. The main objective was to create one hole continuously drilled to a depth of 50 cm. A secondary objective was to drill a second hole using a 'hunt-and-peck' method which involves periodically retracting the drill in an attempt to discern depth-dependent soil characteristics.

The moisture contents for the two soil-only tests were chosen to be 'worst case' in terms of potential soil off-gassing (where 10 percent was the maximum in RESOLVE project requirements). The higher moisture contents gave a larger, more apparent moisture gradient for the desiccation measurements. For the drill tests, 5 percent moisture was chosen to match the lunar surface data from LCROSS (Ref. 1), which indicated a polar water content of 5.6 percent. DT0 and DT1 used this moisture content since it would be the 'worst case' for drilling. The 1 percent content of DT2 was chosen to be a more challenging condition for the NIRVSS instrument detection. DT3 had a stratified (layered) moisture content. The top 5 cm of soil was dry to room conditions (which is around 0.15 percent moisture), the next approximately 10 cm had 5 percent moisture, then alternated dry-wet for 3 more layers, 10 cm each. The lowest 70 cm of the bin was 5 percent moisture. The goal of the stratification was to examine if any depth dependent soil characteristics could be discerned from the cuttings pile.

TABLE 1.—SUMMARY OF THE TEST GOALS

Test name	Date	Pressure	Soil type, moisture percent	Drill status	Objectives
Soil Test 1 (ST1)	Jan 28, 2013	Vacuum	GRC3, 6%	No drill	Soil sampling pre- and post-test to determine vacuum effects on soil.
Soil Test 2 (ST2)	April 8, 2013	Vacuum	Chenobi, 10%	No drill	Soil sampling pre- and post-test to determine vacuum effects on soil.
Drill Test 0 (DT0)	Aug 16, 2013	Open air	LHT, 5%	Core drill, 1 hole: 10 cm	Test drill rig functionality and effectiveness of drill system.
Drill Test 1 (DT1)	Sept 6, 2013	Thermal Vacuum	LHT, 5%	Auger, 1 hole: 40 cm	Test functionality at thermal-vac, examine soil behavior during drilling, hardware thermal measurement for NIRVSS
Drill Test 2 (DT2)	Sept 12, 2013	Thermal Vacuum	LHT, 1%	Auger, Hole 1: 50 cm, Hole 2: 3 pecks at 5 cm	Test with NIRVSS instrument
Drill Test 3 (DT3)	Sept 24, 2013	Thermal Vacuum	LHT, stratified 5% with dry layers	Auger, Hole 1: 55 cm, Hole 2: 4 pecks at 10 cm	Test with NIRVSS instrument

Results

The results of all tests are presented here, summarized per topic area. The discussion begins with a summary of the hardware and system performance in the thermal vacuum environment. Soil characteristics will then be described in terms of moisture content before and after the test. Disturbances of the soil during pump down have been documented in previous publications (Refs. 2 and 3), and observations during these tests will be offered to supplement that data. Finally, observations of the cryogenic drilling operations are offered, including the drilling parameters used, the behavior of the soil, and the characteristics of the cuttings pile.

Thermal Vacuum Hardware Performance

Operationally, this was the first test series utilizing the thermal capabilities of the chamber (the liquid nitrogen cooling on the soil bed as well as the cold shroud). Therefore a discussion of facility and hardware performance is appropriate.

Table 2 is an summary of all of the test parameters. The ‘test pressure’ stated in the table is pressure of the chamber at the time of drilling (or the lowest pressure achieved in the case of the soil-only tests). These vacuum levels can be achieved after 8 hr. This is primarily driven by a deliberately slow pump down to mitigate soil disturbances caused by off-gassing of the soil. The lowest pressure that can be achieved with soil present in the chamber is 1×10^{-6} torr. Tests with higher pressures, such as DT2, were the result of small leaks in the new liquid nitrogen cooling system. Improvements made during this test series should mitigate leaks in future test programs.

The test time indicated in Table 2 encompasses the period of time when the pumps were active (including during drilling). The soil bin remained sealed (tightly capped and wrapped in plastic wrap) before and after vacuum exposure, therefore the time in Table 2 is also the duration during which the soil would be exposed to desiccation. The average soil temperature was taken across the 15 thermocouples embedded in the soil. Cooling of the soil bed was initiated approximately 3 hr after vacuum pump down start. The two soil-only tests were allowed to chill in to steady state conditions, which occurred after 50 hr of liquid nitrogen exposure. However, the chill in times are longer for dry soils. For example DT3 had dry layers, and the thermocouples in these layers showed warmer, higher gradient (radially) temperatures than the wet layers. For operations planning, 48 hr is recommended for soil cooling for this hardware configuration.

The drill rig did face some operational issues at the cryogenic temperatures. After 16 hr of exposure to the cold wall, the motor temperatures for the drill rig reached –70 °C, and the motors were inoperable. While there is evidence in the thermocouple traces that sending power to the motors resulted in some warming, they were unable to move. This first took place in DT1, so the cold wall was deactivated and

TABLE 2.—SUMMARY OF TEST CONDITIONS

Test	Soil type, moisture	Test pressure, torr	Time at vacuum, hr	Average soil temp, °C	Max hole depth, cm	Drill penetration rate, mm/s	Average soil density, g/cm^3
Soil Test 1	GRC3, 6%	1.5×10^{-6}	96	–140	NA	NA	1.57
Soil Test 2	Chenobi, 10%	1.8×10^{-5}	75	–138	NA	NA	1.75
Drill Test 0	LHT, 5%	753	NA	–100	10	0.4	1.46
Drill Test 1	LHT, 5%	1.4×10^{-5}	39[a]	–105	40	0.4	1.46
Drill Test 2	LHT, 1%	1.5×10^{-4}	30	–63	50	0.4	1.53
Drill Test 3	LHT, Stratified 5% with dry layers	9×10^{-6}	79	–120	55	0.1	1.50

Note: Time at vacuum defined as pumps ON
[a]Last pump down in sequence of 3 (two failed pump downs due to leak)

the motors powered periodically until drilling was possible. This occurred when the motor temperatures reached –35 °C. This temperature was likely related to the vacuum compatible lubricant used in the motors (from a previous test series), which was found to be rated to –40 °C. Therefore the motors were wrapped with heaters prior to DT2. Because the lubricant was not impacted by thermal cycling, the motors were allowed to chill and only heated just prior to drilling. The drill operation (rotation and penetration) worked with no issue following this procedure. However, the translation trolley, which controlled lateral positioning of the drill, still faced issues. Only very limited movement was accomplished in DT2 and the system seemed to bind. The motors were clearly operational since the chain drives were observed tensioning when the motors were activated. Therefore, prior to DT3 the translation trolley rollers were removed and the clearance on the axle was increased. The rollers were brass while the axle was stainless steel, so the difference in thermal expansion could have caused binding. The lubricant was also removed from all accessible surfaces and replaced with dry Molybdenum-disulfide powder. Since re-lubrication was not possible within the motors and gearboxes they remained heated. There was still an initial hang up in the translator trolley during DT3 when the motors were first activated. This was overcome after pulsing the motors, and the trolley moved freely with no subsequent issue.

Soil Moisture Content

Since this test series focused on testing and validating the spectrometer, it was important to understand the moisture conditions a priori. However, the act of reaching the environmental conditions needed for the test (the pump down and freezing processes) can change the soil conditions. In attempt to quantify this effect, soil samples were taken before and after thermal vacuum exposure and analyzed for moisture content. For ST1 and ST2, two sets of post-vacuum samples were taken. The first was extracted while the soil was still frozen, immediately after vacuum was broken. A hole saw on a hand drill was used to take core samples of approximately 40 g each. The same hole was repeatedly drilled in 3.5 cm increments to obtain a depth dependent moisture profile down to 20 cm. The depth limit was a function of the arbor size and the ability to safely access the soil within the chamber. The second set of samples were taken in the laboratory after the soil had warmed to room conditions. The 40 g samples were taken at depth increments as soil was removed from the bin. These laboratory ("thawed") samples were also taken for DT1 and DT2. The soil from DT3 has not yet been analyzed and, regrettably, was compromised after a lengthy exposure to ambient conditions during the October 2013 US government shutdown.

The depth dependent moisture profiles are shown in Figure 4. The samples taken while frozen are shown as open symbols with dashed lines, while the solid symbols are the thawed samples. For ST2, four

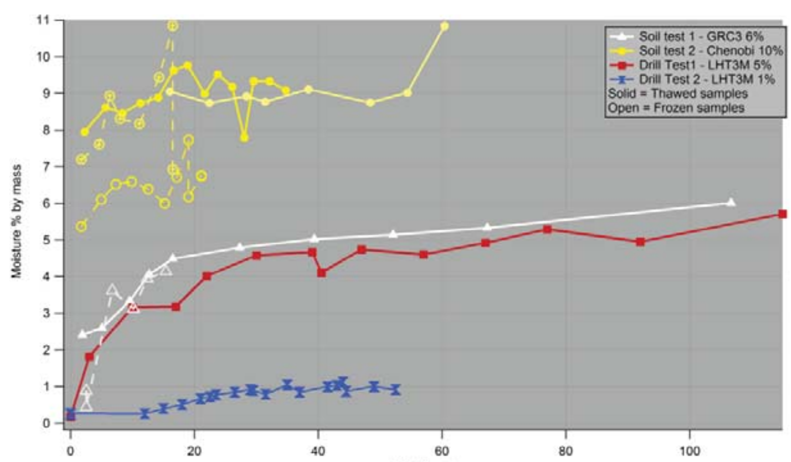


Figure 4.—Depth dependent moisture profiles based on post-test soil sampling. Solid symbols indicate sampling after thaw, open symbols indicate samples of frozen soil.

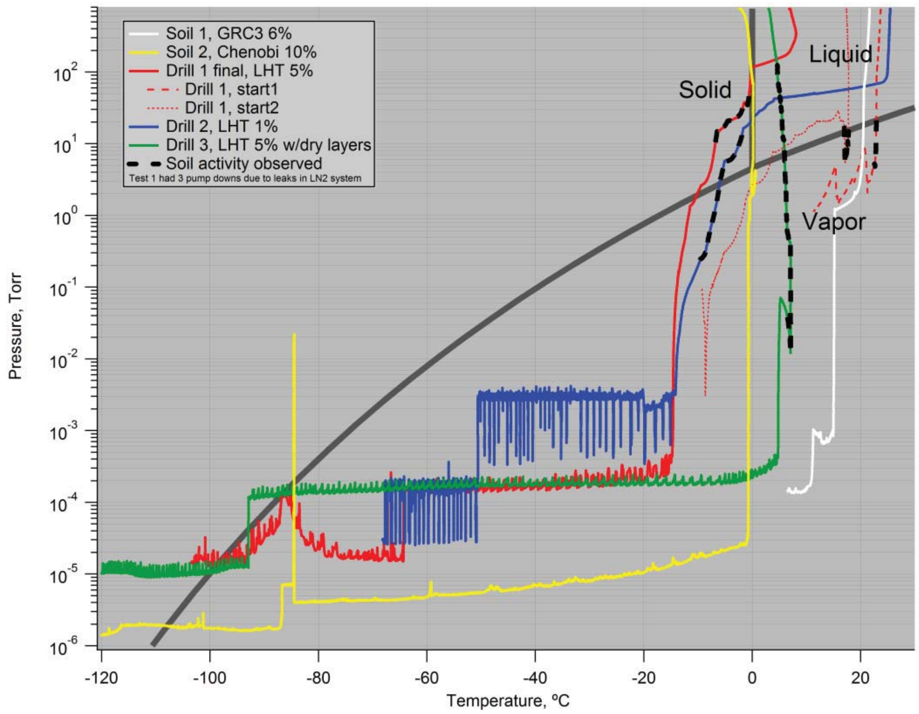


Figure 5.—Pressure versus temperature curves for all tests superimposed over the water phase diagram. The sublimation line is taken from the Murphy&Koop (2005) correlation from Reference 6.

separate holes were drilled (two frozen and two thawed). The samples are quite desiccated near the surface, as expected. Especially for ST1, the frozen and thawed moisture profiles began to converge at the greater depths. As the soil thawed, the surface layer wicked moisture from the lower layers, so this distribution makes sense. There was a peak moisture in the frozen samples around 8 cm depth for all tests, which is a curious and yet unexplained observation. The data from ST2 is quite irregular and while the trend is similar between the two frozen samples, the magnitudes are different. Non-homogeneities are not uncommon in soil beds (despite best efforts otherwise) so it is possible that this difference is real. No other readily apparent variations in either procedure or conditions explain this discrepancy.

The pressure versus temperature plots for the vacuum tests are shown superimposed over the water phase diagram in Figure 5. In order to retain the most moisture in the sample during the pump down process, the ideal scenario would be to simultaneously reduce pressure and temperature to follow the sublimation curve. Operationally this is feasible but difficult. In order to avoid condensation of atmospheric moisture, liquid nitrogen cooling should not be activated until pressures are in the 10 torr range. In DT1 and DT2 the cooling was activated at 350 and 90 torr, respectively, and frost was visible in both tests. Prior to installation in the chamber, the simulant is pre-chilled in a commercial freezer to –20 °C. The transport and installation of the simulant into the chamber takes about 1 hr. Therefore the soil must be exposed to room temperature conditions (thus would be warming) until this pressure level is reached. The only way to stay within the solid regime would be to reduce pressure at a rate coincident to the warming of the soil (similar to ST2). However, pressure reduction of the chamber must be performed slowly to avoid pressure differentials across the soil bed that can cause large scale soil disruptions (Refs. 2 and 3). These disruptions can still occur (indicated by the black dashed line in Figure 5, discussed in the next section) but are highly mitigated using a slow pump down. The steep drop in the pressure that occurs at 1 torr is the result of the turbomolecular (‘turbo’) pump activation. This type of pump is very effective in the 1 to 10^{-6} torr range for this chamber, and has the added benefit of unattended operation. So in order to follow the sublimation curve, pressure should be maintained at 1 torr, just before the turbo pump, until the soil can chill to –50 °C. This would significantly increase the time scale of the test

because the roughing pump would need to be monitored while the soil chilled and the chill could take longer since the pressure in the chamber would be higher.

Despite the significant time spent in the vapor phase region, indicating evaporation would be occurring (vacuum times for each test are indicated in Table 2), desiccation of the sample was limited to a surface layer. As indicated in Figure 4, the top 20 cm (8 in.) of the thawed sample showed evidence of drying. While there would have been redistribution during the thaw process, the frozen sample data from ST1 supports desiccation having been confined to within 20 cm of the surface. Considering the lunar surface itself, desiccation of the surface layers is a realistic expectation.

Soil Disturbances

One concern related to vacuum testing of soil simulants is the soil disturbances that can occur during the pump down process. This phenomenon was discussed in more detail in Reference 3. During that program, the disruptions ranged from large scale soil eruptions (e.g., a large 'tidal wave' of soil propagating across the surface) to small soil spouts that resembled water boiling. These disruptions could be mitigated by reducing pressure decay rate, which effectively decreases the pressure differential within the soil bed. These mitigation techniques were employed during this test series. Small scale disturbances were still observed in all three drill tests using LHT-3M simulant. Figure 6 shows two smaller scale 'spouts' from DT3. However, disturbances were not seen in the soil-only tests using GRC3 and Chenobi. This is not a simulant specific issue, however, since disturbances were observed with GRC3 simulant in Reference 3.

The most interesting case of this test series was DT3. A small scale soil disturbance continued constantly from 100 torr down to 0.01 torr. In every other test to this point, soil activity ceased by 1 torr, which suggested there was a low pressure threshold to this phenomenon. The pressure versus time plot from DT3 is shown in Figure 7. The region of soil activity is highlighted in grey. Starting at atmospheric pressure (point A) pressure reduction was achieved using a venturi pump. The slow pressure decay generated by this pump has been demonstrated to be sufficient to eliminate soil disturbances. However this pump was only good to 100 torr (its lowest achievable pressure is 30 torr after 4 hr). At point B (100 torr) a roughing pump (displacement pump) was started. Gaseous nitrogen was bled into the vacuum line and into the chamber itself to reduce pressure decay rate in the chamber. Despite this proven technique, a small 'boiling' type disturbance was triggered. The gaseous nitrogen bleeds were regulated manually for two hours to mitigate the disturbance while still making forward progress. Even at point C, when the pumps were temporarily deactivated, the disturbance continued. At point D the turbo pump was activated, working under the assumption that the soil activity would cease once a low threshold was reached. However, the soil disruption continued and even slightly increased in intensity. At point E the pump was deactivated. When pressure began to rise the soil activity ceased. At point F the turbo pump was reactivated, pressure dropped and the soil remained calm. No more disturbances were observed.

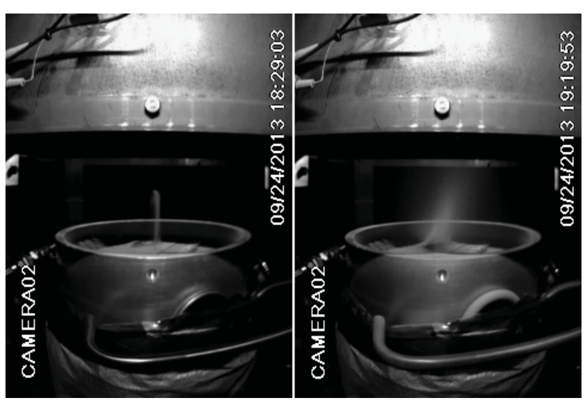


Figure 6.—Soil disturbances (spouts) during pump down of Drill Test 3.

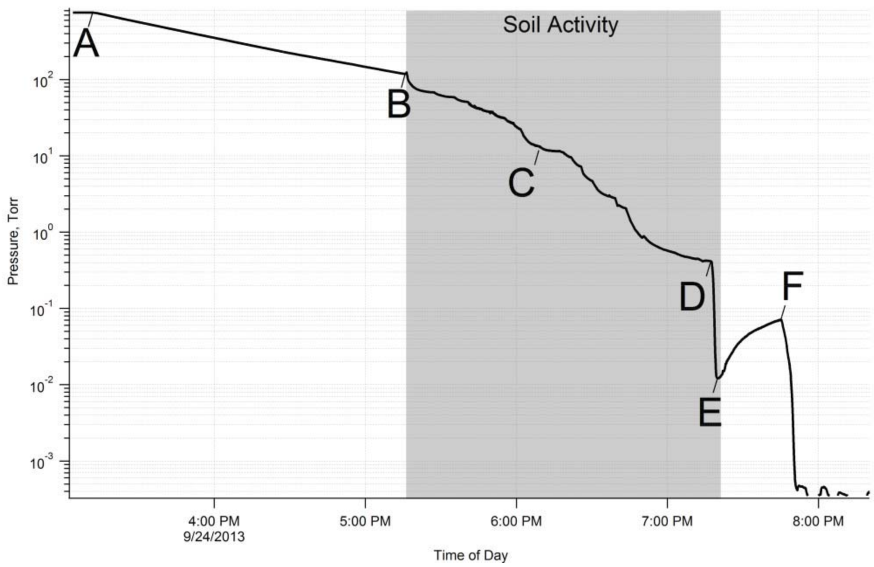


Figure 7.—The pressure versus time plot of the Drill Test 3 pump down. The grey area indicates the period where soil disturbances were observed. A: activation of the venturi pump, B: activation of the displacement pump, C: brief deactivation of all pumps, D: turbo pump active, E: all pumps off, F: turbo pump active.

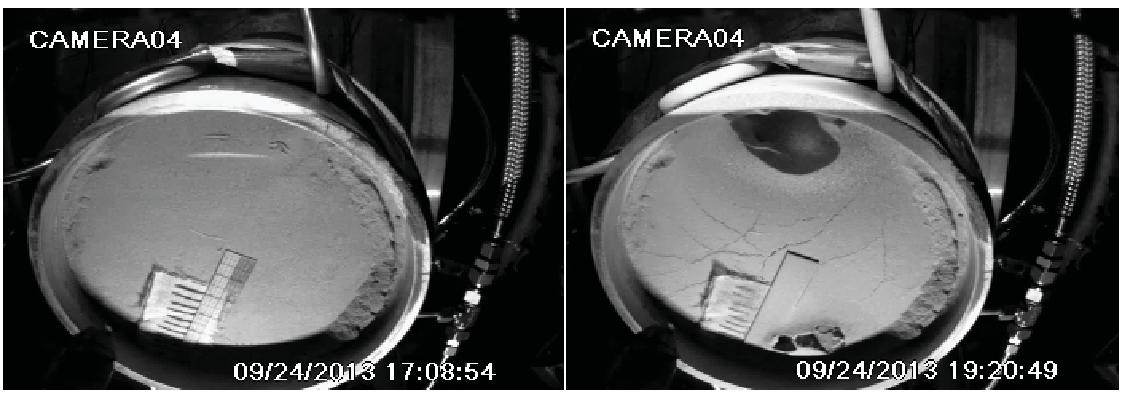


Figure 8.—The soil surface of drill test 3 before (left) and after (right) soil disturbances.

A detailed, focused study of this phenomenon has not been performed. Only observational data exists, so it is difficult to pinpoint the reason soil disturbances occur in some cases and not others. The stratified moisture content of Drill Test 3 (a dry top layer with a wet layer underneath) may have played a role in the unique behavior. The aluminum foil barrier used to isolate the layers could also have restricted gas permeation through the soil. The soil disturbances in DT3 were localized near the wall (Fig. 8), where there would be a path between the foil and the wall for the gases to escape. Thus the disturbance could be more severe at a localized gas path location. Cooling of the soil bed was also delayed in this test since frost buildup was observed inside the chamber in DT2. Maintaining a colder soil bed during pump down did reduce soil disruptions (or at least significantly decrease their intensity) in previous tests.

There was a concern prior to this test program that trapped subsurface gases may be released suddenly upon drill penetration. No soil disruptions were observed during drilling operations. While the NIRVSS instrument did detect gas release during drilling, it was of insufficient pressure to cause soil disturbances. Similarly, no soil disruptions occurred at these low pressures when using the cone penetrometer in Reference 3.

Drill Behavior

The primary goal of these tests was simply to penetrate the subsurface and create a hole and pile of cuttings to analyze with the spectrometer. Strictly speaking, this was not a test of drill performance. However some observations can be made regarding the ability to drill into a cryogenically frozen soil bed.

The drilling parameters for this test were based on recommendations from the field demonstration tests (Ref. 7). The drill rotational speed was 25 rpm for all tests. The penetration rate was 0.4 to 0.1 mm/s depending on test needs. The drive system (motor gearing and drive screw) provided weight on bit of approximately 100 lb, though this was not explicitly measured.

In DT0, an off the shelf drill tool was used. This open air test was intended to test the functionality of the drill system while exploring initial challenges of cryogenic soil drilling. The tool was a 3/4 in. diameter, 24 in. long rebar cutter and was open-cored up to 9 cm. There was no core sampling requirement to this test program, so the use of the coring tool in this test was an instance of opportunity. The penetration speed was set to 0.4 mm/s, but once it met soil resistance the actual penetration was 0.1 mm/s. After the core filled, the drill struggled to progress further. Upon removal from the hole, the coring tool retained the sample, as evidenced in Figure 9, which shows the bit as well as the clean-out holes filled with soil. The soil was doped with 5 percent moisture. While this observation offers support that a coring tool can retain a cryogenically frozen sample, the test was performed in ambient pressure conditions, thus the tool was at room temperature prior to penetration. The heat transfer would affect both drill performance and sample retention. Additionally, the cuttings (Fig. 9(A)) are clumped, also indicating a thawed sample.

All other drill tests used a 2.5 cm diameter, 100 cm long auger tool, with no open core. All drilling with this tool was performed in full thermal vacuum conditions, meaning both the tool and soil were exposed to near liquid nitrogen (100 K) temperatures. With this tool, the penetration rate did not change when it met soil resistance, but stayed very consistent throughout penetration. Figure 10 shows a sequence of images of the cuttings pile during the drill of hole 1 in DT3. The depth of the drill is shown below each image. The cuttings pile is quite tall during penetration and begins to settle as soon as the drill is retracted. The bright lamp, required for the NIRVSS instrument, makes it difficult to resolve small features, but there is possible evidence in the 50 cm image of soil clumping. The final image shows the soil retention on the auger after it was retracted from the hole 2. In all tests, the auger continued to rotate any time it was in the hole to avoid binding, so the auger rotated until it was fully retracted. There were no brushes nor percussion with this drill, so the amount of retention is not surprising. DT2 with only 1 percent moisture in the soil had significantly less retention.

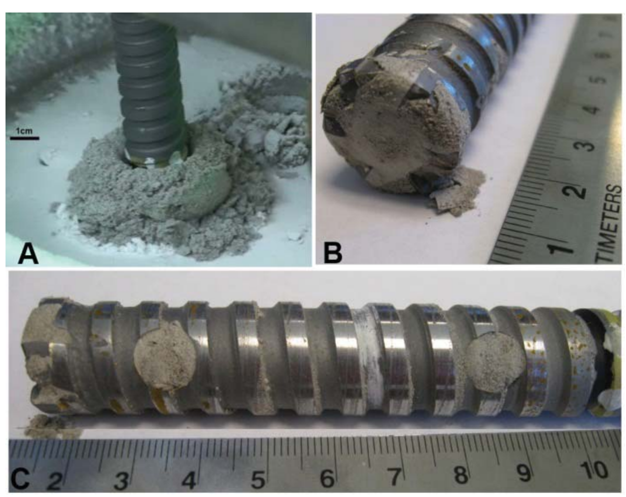


Figure 9.—The drill tool used in Drill Test 0. (A) the cuttings pile of the 10 cm hole, (B) the filled core, (C) the clean out holes of the core section shown filled with simulant.

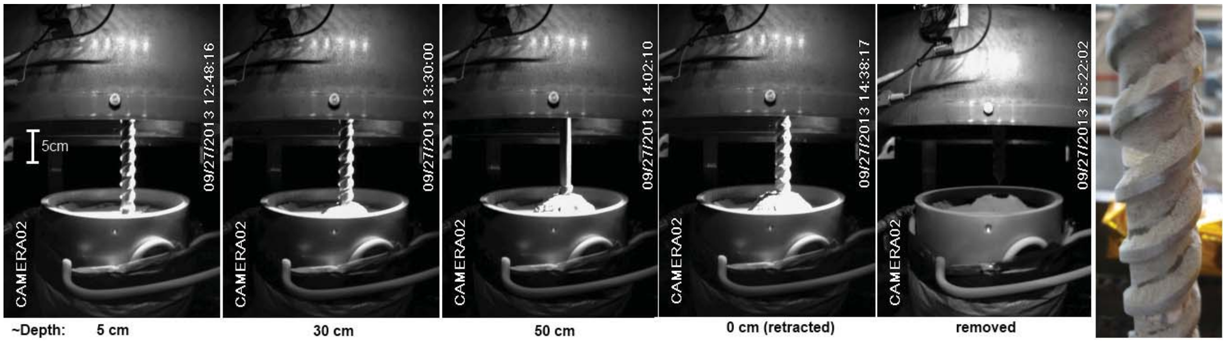


Figure 10.—A sequence of images during Drill Test 3. The depth of the bit is shown below the images. At far right, the auger after the test with simulant retained on the flights.

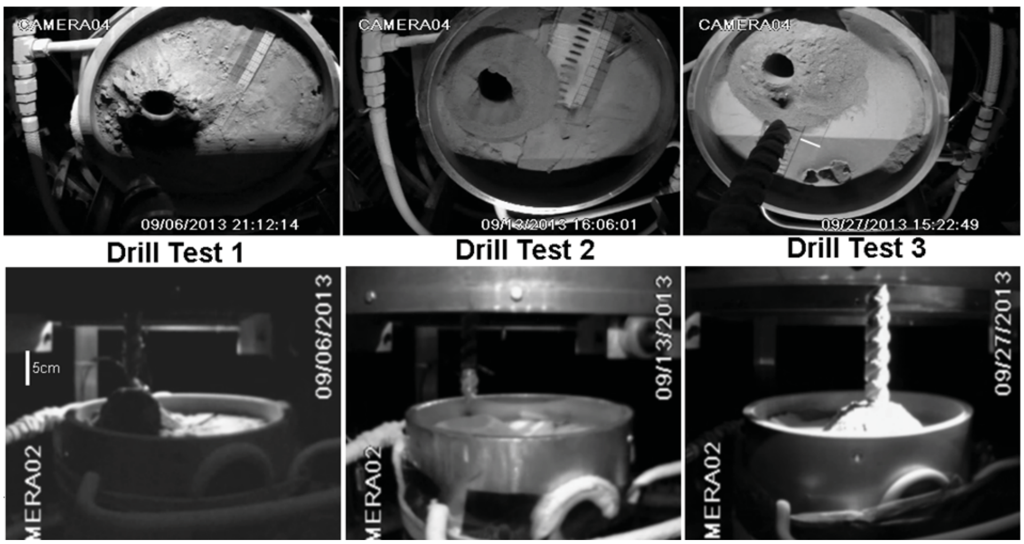


Figure 11.—Images of the cuttings pile from each test shown just after the drill has been retracted. The top set of images is a top-view of the soil surface, while the bottom set is a side-view looking across the soil surface. The angle of repose measurements were taken using the lower set of images.

Figure 11 shows images of the cuttings piles from all three drill tests. All images were taken just after the drill was retracted from the hole. Due to the hardware positioning, the angles of the light sources cast severe shadows on the soil surface, and could exaggerate small features. This is particularly true in the images from DT1. The lighting was improved in DT2 and DT3. The top-view images indicate the structure of the hole and the horizontal size of the cuttings pile. In DT1 and DT3 the drill hole has retained its structure (did not collapse). Most of the settling of the cuttings pile observed in the video involved a widening of the cuttings pile, as opposed to back filling of the hole. However in DT2, which only had 1 percent moisture, there was inward collapse of the hole during retraction of the drill. The angle of repose was measured using the side view images of Figure 11. The resolution of these videos was not ideal, but the measured angles were approximately: 50° for Drill Test 1 with 5 percent moisture, 20° for Drill Test 2 with 1 percent moisture, and 30° for Drill Test 3 with layered 5 percent per dry soil.

Conclusion

An environmental test facility has been developed to conduct hardware tests simulating lunar polar conditions. Both the soil bin and the facility itself are cooled using liquid nitrogen to achieve full thermal vacuum conditions for both the hardware and the soil. Operationally, a vacuum of 9×10^{-6} torr can be achieved in this facility with both thermal shroud and soil present. The pacing element for test time is the

chill-down of the simulant. Using a 1 m deep, 28 cm diameter soil bin approximately 48 hr should be allowed to reach the steady state simulant temperature of –130 °C. Higher moisture content soils require less time than dry soils.

The act of achieving a vacuum environment can change the conditions of the regolith simulant. This includes off-gassing of the simulant which can cause movement, or disturbances in the simulant bed. This has been observed in previous tests, and regulating pressure decay can mitigate this effect. For moisture doped simulant, the vacuum pump down can also lead to drying of the soil. Pre- and post- test sampling of the simulant bed was performed to determine the extent of this desiccation as a function of depth. Even with long vacuum exposure times (4 days) the desiccation was primarily restricted to the top 20 cm of simulant. A dry surface layer such as this would be a realistic expectation for lunar conditions.

Cryogenic drilling operations were performed in a thermal vacuum system using an auger. The goal of these tests was to examine the behavior of the drill and the simulant, with a particular focus on the characteristics of the cuttings pile. A spectrometer instrument was used in the latter two tests to analyze water signatures from the cuttings piles. The highest soil moisture content used in these drill tests was 5 percent. Using 25 rpm and a penetration rate between 0.4 and 0.1 mm/s, the drill was able to penetrate the 50 cm required for the tests with no issue. The low speeds were chosen based on previous field experience to avoid binding. The low penetration rate also facilitated higher resolution data for the spectrometer instrument. Two drill holes could be achieved per test. The first was a continuous drill while the second hole involved retracting the drill to the surface at intervals. This hunt-and-peck approach was tested as a possible means to detect depth dependent moisture characteristics. The results from the spectrometer will be included in a separate publication of the spectrometer data by project partners.

Using visible images of the simulant surface, characteristics of the cuttings pile could be observed. For LHT-3M simulant with 5 percent moisture content the angle of repose was as high as 50°, while 1 percent moisture resulted in a 20° angle. The cuttings piles all began to settle immediately after the auger was removed. Some possible soil ‘clumping’ may have been present in the 5 percent simulant, but the severe lighting angles tended to exaggerate the features.

In addition to verification testing of the NIRVSS spectrometer, this test series has provided valuable experience with simulant at lunar polar conditions. The modifications and improvement made to both the facility and the drill rig to create this environment will enable future component and integrated testing. VF-13 is currently the largest ‘dirty’ thermal vacuum chamber available for cryogenic excavation use.

References

1. Colaprete, A., et al., 2010, “Detection of Water in the LCROSS Ejecta Plume,” Science, 22, 463–468.
2. Kleinhenz, J.E. and Wilkinson, A., 2012, “ISRU Soil Mechanics Vacuum Facility: Soil Bin Preparation and Simulant Strength Characterization,” 50th Aerospace Sciences Meeting and Exhibit. American Institute for Aeronautics and Astronautics. AIAA–2012–0359.
3. Shaw, K., “Post Test Summary Report JSC1-a Facility Assessment Testing,” NASA GRC White paper, 2009.
4. Kleinhenz, J.E. and Linne, D., 2013, Preparation of a Frozen Regolith Simulant Bed for ISRU Component Testing in a Vacuum Chamber, 51st Aerospace Sciences Meeting and Exhibit. American Institute for Aeronautics and Astronautics. AIAA–2013–0732. NASA/TM—2013-217833.
5. ASTM Standard D2216-05, “Standard Test Methods for Laboratory Determination of Water (moisture) Content of Soil and Rock by Mass,” ASTM International, West Conshohocken, PA.
6. Andreas, E.L. “New Estimates for the Sublimation rate for Ice on the Moon,” Icarus 186, 24–30, 2007.
7. Boucher, D.S. “Development and Testing of the RESOLVE Sample Acquisition System,” 51st Aerospace Sciences Meeting and Exhibit. American Institute for Aeronautics and Astronautics. AIAA–2013–0439.